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Propulsion System/Flight Control Integration and Optimization

Flight Evaluation and Technology Transition

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PROPULSION SYSTEM-FLIGHT CONTROL INTEGRATION- FLIGHT EVALUATION AND TECHNOLOGY TRANSITION

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Abstract

Integration of propulsion and flight control systems and their optimization offers significant performance improvements. The NASA Ames Research Center, Dryden Flight Research Facility has, over the years, conducted research programs which have developed new propulsion and flight control integration concepts, implemented designs on high-performance airplanes, demonstrated these designs in flight, and measured the performance improvements. These programs, first on the YF-12 airplane, and later on the F-15, have demonstrated increased thrust, reduced fuel consumption, increased engine life, and improved airplane performance; with improvements in the 5- to 10-percent range achieved with integration and with no changes to hardware. The design, software and hardware developments, and testing requirements have been shown to be practical. This technology has been transferred to the user community through reports, symposia, and industry cooperative programs, and is appearing on operational and advanced airplanes. The flight evaluation and demonstration have been shown to be key in maturing the technology and hastening its transition into production.

Nomenclature

ADECS adaptive engine control system
 AJ jet primary nozzle area, ft^2

Ames-Dryden

a_n
CAS
CDP
CENC
CIVV
DEEC
DEFCS

EEL
EMD
EPR
FNP
FTIT
 H
HIDEC

M
 $N1$
 $N2$
PB
PLA
 $PS2$
PSC
 $PT2$
 $PT6$
RCVV

Ames Research Center, Dryden
Flight Research Facility

normal acceleration, g
control augmentation system
component deviation parameters
convergent exhaust nozzle control
compressor inlet variable vane, deg
digital electronic engine control
digital electronic flight control system
extended engine life
engine model derivative
engine pressure ratio, $PT6/PT2$
net propulsive force, lb
fan turbine inlet temperature, $^{\circ}\text{F}$
pressure altitude, ft
highly integrated digital electronic control
Mach number
fan rotor speed, rpm
core rotor speed, rpm
burner pressure, lb/in^2
power lever angle, deg
fan inlet static pressure, lb/in^2
performance seeking control
fan inlet total pressure, lb/in^2
turbine discharge total pressure, lb/in^2
rear compressor variable vane, deg

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$TT2$	fan inlet total temperature, °F
WA	airflow, lb/sec
WF	fuel flow, lb/hr
$WFAB$	augmentor fuel flow, lb/hr
$WFGG$	gas generator fuel flow, lb/hr
α	angle of attack, deg
β	angle of sideslip, deg
Δ	change in parameter

Introduction

Integration of propulsion control systems and propulsion-flight control systems has been shown to produce significant improvements in airplane performance parameters such as thrust, range, and rate of climb. When systems are not integrated, each must be able to operate in a worst-case combination with the other systems, thus requiring large operating margins. Integration allows these margins to be reduced at times when the full margins are not required, resulting in improvements such as higher thrust, lower fuel flow, or greater maneuverability and range. Integration control laws may be developed in an off-line process, and stored in an onboard computer for implementation. System performance could be further improved if a real-time optimization could be used in place of the *a priori* or preprogrammed optimization. This latter approach is much more challenging to develop and implement, but, because it can be designed to adapt to flight conditions, it may be able to achieve higher levels of performance.

In the mid-1970's, propulsion system digital control and control integration were developed and demonstrated in the integrated propulsion control system (IPCS) program, a joint USAF/NASA program flown on an F-111 airplane.¹ The flight demonstration clearly showed the benefits of digital control and control integration. In the late 1970's, a digital cooperative control system was flown on the NASA YF-12C airplane. This system integrated the inlet control, autothrottle, airdata and navigation functions, and resulted in dramatic improvements in flightpath control and range, even though the integration was not optimized.² This technology was used when the concept was implemented on the SR-71 fleet. Digital control of the F100 engine was flight demonstrated on the NASA F-15 airplane in the digital electronic engine control (DEEC) program.³ The decision to use DEEC tech-

nology for the F100 engines was made shortly after the NASA flight evaluation.

Based on the promising results of the previously mentioned programs, the NASA Ames Research Center, Dryden Flight Research Facility (Ames-Dryden) has established a research program for control integration. The F-15 airplane was equipped with DEEC, a digital flight control system, digital inlet controls, and computers and interfaces to provide a flight research facility with excellent capabilities, called highly integrated digital electronic control (HIDEC). Integration between the engine control and flight control systems was implemented⁴ followed by the addition of inlet control integration.⁵ The YF-12 cooperative control system, DEEC, and HIDEC used preprogrammed schedules optimized for a nominal or known engine state. In the next phase of the HIDEC program, a performance seeking control (PSC) system that provides for onboard optimization will be implemented and flown. Another future use of propulsion and flight control integration may be propulsion-enhanced flight controls for emergency landings with major flight control failures, such as total hydraulic system failure.

This paper will provide an overview of propulsion-flight control integration, and demonstrate the importance of flight research in moving the technology from the laboratory to production. The importance of flight in the transition of technology for the YF-12 cooperative control and DEEC programs will be given. The NASA F-15 HIDEC program will be described, along with the plans and performance predictions for the PSC program.

Integrated Propulsion-Flight Control Research

Digital flight control, digital propulsion control, and integrated flight-propulsion control research, conducted on the YF-12 and F-15 airplanes at NASA Ames-Dryden will be described in the following sections.

YF-12 Flight Research

As mentioned previously, NASA has conducted a research program on flight control systems and propulsion system-flight control interactions on the YF-12 airplane. High speed supersonic cruise at Mach numbers greater than 2.5 and altitudes above 70,000 ft have highlighted many new airframe-propulsion system interdisciplinary problems which impact efficient aircraft operation. High speed cruise flight led to the

requirement and development of variable geometry mixed compression inlets with control loops consisting of airframe and propulsion system feedback variables. This led to pronounced effects on the stability and control of the aircraft. In addition, atmospheric characteristics at high altitude and high-speed cruise conditions introduced problems not normally encountered with lower speed-altitude cruise flight. The primary difference is the significantly faster rate at which a supersonic cruise aircraft traverses atmospheric effects such as temperature, pressure, and wind changes. High-temperature and supersonic flow, and rarefied atmospheric conditions also contribute to measurement problems both in terms of absolute value and resolution. These aerodynamic and atmospheric characteristics can affect aircraft flightpath control significantly.

The NASA YF-12 flight research program addressed many of the previously mentioned issues concerning supersonic cruise at flight to Mach 3.0 and 80,000 ft, during a sequence of research programs: (1) flight measurement of airframe-propulsion system interactions, (2) development and flight test of flightpath control modes including the addition of an autothrottle, (3) the design of a cooperative aircraft-propulsion control system, and (4) installation of a digital control system incorporating inlet, autopilot, autothrottle, airdata, and navigation functions.

Airplane Description

The YF-12 airplane (Fig. 1) is a twin-engine, delta winged airplane designed for long range cruise at Mach numbers greater than 3.0 and altitudes above 80,000 ft. Two nacelle-mounted, all movable vertical tails provide directional stability and control. Two elevons on each wing, one inboard and one outboard of each nacelle, perform the combined function of elevators and ailerons. The airplane is normally operated with the stability augmentation system engaged to provide artificial stability in pitch and yaw and damping in pitch, yaw, and roll.

The airplane has two axisymmetric, variable-geometry, mixed compression inlets, which supply air to two J58 engines. Each inlet has a translating spike and forward bypass doors. An automatic inlet control system varies the spike and bypass door positions. The spike position is scheduled with flight conditions to set the throat Mach number. The bypass doors are controlled by a closed-loop system as a function of flight conditions and duct pressure to position the terminal

shock wave in the optimum position subject to inlet stability constraints.

Airframe-Propulsion System Interactions

Automatic inlet operation affects both the longitudinal and lateral-directional characteristics of the airplane. In the longitudinal mode, the thrust-drag changes associated with the automatic inlet operation significantly degrade long period-phugoid characteristics.⁶ This in turn can adversely affect the flightpath control task. Adding atmospheric variations such as a temperature change further complicates the problem by inducing effective thrust changes. With the very long response times involved, pilot induced oscillations are a potential problem.

Lateral-directional interactions of the airframe with the propulsion system are very pronounced on the YF-12 airplane at high-speed cruise flight conditions. Aircraft response tests were made using a rudder pulse with the stability augmentation system off for both inlets fixed and inlets automatic operation. With the inlets fixed, the dutch roll damping of the aircraft is stable; however, engaging the automatic inlet control mode makes the system unstable. Flight data was analyzed to determine the forces and moments induced by the inlet geometry. Results indicate that the inlet geometry has the same order of effectiveness as the ailerons and rudders.⁷ Analyses have been performed illustrating how inlet geometry can be used to augment lateral-directional airplane stability, thus an integrated approach to airframe-propulsion system control in the area of stability augmentation can lead to a reduction in control surface size.

Altitude Control

Precise flightpath control is required for both satisfactory ride qualities and maximum airplane performance. Accurate control of altitude and Mach number becomes increasingly difficult at high-speed, high-altitude conditions caused by decreased aircraft stability, low static pressures, and atmospheric disturbances. The original autopilot did not have an altitude hold mode capable of operation at Mach 3.0 flight conditions. Pilot control of the altitude ranged from hundreds to thousands of feet depending on atmospheric flight conditions. Therefore, an early objective of the YF-12 research program was to develop an autopilot mode capable of accurate altitude control at altitudes above 70,000 ft.

A key element in the development of the altitude hold control mode was to obtain altitude information from an airdata source. This presented three issues: (1) low transducer resolution caused by the high-altitude flight conditions (12-ft resolution at 77,000-ft altitude), (2) measurement lag of approximately 1.5 sec at this altitude condition, and (3) sensitivity of noseboom static pressure measurements to angle of attack (angle-of-attack changes appear as altitude changes).

A high-fidelity simulation was developed to represent the many nonlinear aspects of the overall altitude control problem. Detailed models of all the elements affecting altitude control were contained within this simulation. The simulation included the three degrees of freedom, inlet geometry effects on aircraft motion, inlet operating effects up to the unstart boundary, the characteristics of the afterburning mode of the engines, and the variation of density with altitude. This simulation was found to be an absolute requirement to design an acceptable altitude hold system for the actual airplane.

Typical flight-test data⁸ with the altitude hold mode engaged showed that altitude was held constant to within 25 ft for the 4-min duration; remarkable considering the resolution of the altitude measurement. The altitude hold mode worked well even when decelerating, in one case slowing by 0.4 Mach.

Speed-Mach Control

The YF-12 airplane had a Mach hold control mode which worked through pitch control; if the aircraft slowed down, a pitch down command resulted and vice versa. As such, the mode was very sensitive to small atmospheric disturbances; while Mach number may have been held reasonably closely, it was at the expense of significant pitch maneuvering resulting in a rough ride in terms of normal acceleration. Since many cruise applications require simultaneous altitude and Mach control, a speed control effector in addition to pitch control was required. As such, NASA supported the development and flight test of an autothrottle controller in conjunction with a new Mach hold mode which worked through the autothrottle. This new autothrottle-Mach hold capability was designed to work simultaneously with the previously discussed altitude hold mode. A diagram of the system after improvements were incorporated is presented in Fig. 2. As with the altitude control, atmospheric characteristics and airdata measurements are critical factors in

accurate Mach control. The same high-fidelity simulation developed for the altitude hold development task was also required for the autothrottle-Mach hold development task.

A flight-test example of the autothrottle controlling Mach number along with the altitude hold mode engaged is presented in Fig. 3 at a flight condition of Mach 3.0 and 72,500-ft altitude. The atmospheric conditions were considered to be smooth and the combined systems capabilities were evaluated a number of ways in this example. The autothrottle was engaged in Mach hold while the airplane was stabilized in a 36°-bank turn. Shortly after engagement, the pilot rolled the airplane to wings level. Approximately 2 min into autothrottle operation, the pilot commanded a 0.023 Mach reduction; the relatively slow response was caused by the throttles being in the minimum afterburning position. During the stabilized portion of the run, speed was held to approximately 0.01 Mach of the desired value. Altitude hold was on throughout the autothrottle operation. The ride qualities of the combined system, as indicated by the normal acceleration, were very good.⁹

The combination of altitude hold and autothrottle Mach hold provided the most stable aircraft platform yet demonstrated at high altitude, Mach 3.0 flight conditions. This research activity demonstrates the technology is in hand for application to any similar stable platform or commercial requirement.

Integrated Controller Design

A wide range of potential benefits may be realized by development of an integrated-cooperative control system for supersonic cruise vehicles. The benefits range from improved inlet stability, reduced engine temperatures, propulsion system drag and trim drag reduction, weight reduction, and control surface size reduction.

Studies were initiated by NASA to develop integrated control concepts and thereby validate some of the benefits discussed. One NASA-supported design study had the objective of developing an integrated lateral-directional augmentation system using inlet controls. This study was based on the previously discussed airframe-propulsion system interactions and force and moment measurements.

Results of the study indicated that incorporation of inlet control geometry in lateral-directional stability augmentation was effective in increasing dutch roll

damping. This increase in dutch roll damping was accomplished while still maintaining inlet unstart protection even in moderate to heavy turbulence. (An unstart is an aerodynamic phenomena in which the terminal normal shock wave moves suddenly from the inlet throat to the cowl lip.) The study also showed that using the propulsion system to augment the flight controls would result in reducing the takeoff gross weight of a supersonic cruise aircraft design by up to 7 percent.

Flight Demonstration of a Cooperative Control System

Several of the separate analog-mechanical control systems of the NASA YF-12 research airplane were replaced by a cooperative digital control system.¹⁰ All of the functions shown in Fig. 2 (inlet control, autopilot, autothrottle, airdata and, in addition, the navigation functions), were performed in a single computer. The central digital computer control provided more accurate computations and faster response. The improved altitude and Mach hold autopilot logic was incorporated. Airdata computations were improved, and lag compensation was applied. In addition, more precise inlet control was obtained with the digital system, and inlet stability margins were reduced.² The overall result of the flight research was that range was increased by 5 percent. Altitude control capability was improved by an order of magnitude as compared to manual control.

Implementation on the SR-71 Fleet

Based on the success of the digital flight-propulsion control system on the YF-12 airplane, the SR-71 fleet incorporated the cooperative control system concepts as part of a major avionics upgrade.¹¹ In fleet use, this system realized range improvements of 7 percent, and eliminated the occurrence of inlet unstarts. Thus, the flight demonstration served to speed the transition of the technology developed in the YF-12 flight-propulsion control research to the operational SR-71 fleet.

F-15 Flight Research

Based on the significant performance improvements found from control integration on the YF-12 program, and the desire to work the control integration issues on a highly maneuverable fighter-class airplane, a research program was developed using the NASA F-15 airplane.

Airplane Description

The NASA F-15 airplane, Fig. 4, is a high-performance, air-superiority fighter aircraft with excellent transonic maneuverability and a maximum Mach capability of 2.5. It is powered by two afterburning turbofan engines. The F-15 airplane provides a complementary testbed airplane to the supersonic cruise YF-12 airplane.

Flight Control System

The F-15 airplane is normally equipped with a mechanical flight control system and an analog control augmentation system (CAS). For the HIDEK and PSC tests, the analog CAS was replaced with a digital electronic flight control system (DEFCS). This system duplicated the analog CAS functions and also had excess capacity which was used for integrated propulsion-flight control. The DEFCS is a dual-channel fail-off system, programmed in Pascal. It has a Mil-Std1553A data bus interface to facilitate interfacing to other aircraft systems.¹²

Engine and Digital Electronic Engine Control

The F100 engine, Fig. 5, is a low-bypass ratio, twin-spool, afterburning turbofan engine. The three-stage fan is driven by a two-stage, low-pressure turbine. The 10-stage, high-pressure compressor is driven by a two-stage turbine. The engine incorporates compressor inlet variable vanes (CIVV) and rear compressor variable vanes (RCVV) to achieve high performance over a wide range of power settings; a compressor bleed is used only for starting. Continuously variable thrust augmentation is provided by a mixed flow afterburner and a variable area convergent-divergent nozzle. For the DEEC program, the F100-PW-100 engine was used. This engine is the production engine for F-15 and F-16 airplanes.

For the HIDEK and PSC programs, a derivative of the F100 engine, the F100 EMD (company designation PW1128) was used. The F100 EMD incorporates a redesigned higher airflow and pressure ratio fan, improved materials in the high-temperature section, and a redesigned 16-segment augmentor.

The DEEC system is a full-authority system for the F100 engine which controls the major controlled variables on the engine, and replaces the standard F100 engine control system. The DEEC is engine-mounted and fuel-cooled, and consists of a single-channel digital controller with selective input-output redundancy, and a simple hydromechanical secondary control.

The functions of the DEEC system are shown in Fig. 6. The DEEC system receives inputs from the airframe through the power lever angle (PLA) and Mach number (M). Engine inputs are received from pressure sensors; fan inlet static pressure ($PS2$), burner pressure (PB), and turbine discharge total pressure ($PT6$); temperature sensors, fan inlet total temperature ($TT2$), and fan turbine inlet temperature (FTIT), rotor speed sensors for the fan ($N1$) and compressor ($N2$). It also receives feedbacks from the controlled variables through position feedback transducers indicating variable vane (CIVV and RCVV) positions, metering valve positions for gas-generator fuel flow ($WFGG$), augmentor fuel flow ($WFAB$), augmentor segment-sequence valve position, and exhaust nozzle position (AJ). The input information is processed by the DEEC computer to schedule the variable vanes (CIVV and RCVV), position the compressor start bleeds, control $WFGG$ and $WFAB$, position the augmentor segment-sequence valve, and control the AJ area. This logic provides linear thrust with PLA, rapid and stable throttle response, protection from fan and compressor stalls, and keeps the engine within its operating limits over the full flight envelope.

The DEEC logic provides open-loop scheduling of the CIVV, RCVV, start bleed position, and augmentor controls. The DEEC incorporates closed-loop control of airflow (WA), implemented through $N1$, and engine pressure ratio (EPR). The closed-loop logic eliminates the need for periodic trimming and improves thrust and transient response. The two main control loops are shown in Fig. 7. The upper part of the figure shows the airflow logic, in which $WFGG$ is controlled to maintain the scheduled fan speed, and hence, airflow. Proportional plus integral control is used to match the $N1$ request to the sensed $N1$. Limits of $N2$, FTIT, and PB are maintained. Shown in the lower part of Fig. 7 is the EPR loop. The requested EPR is compared with the measured EPR, based on fan inlet total pressure ($PT2$) and $PT6$, and, using proportional plus integral control, the nozzle is modulated to achieve the requested EPR. The EPR control loop is only active for intermediate power operation and augmentation. At lower power settings, a scheduled nozzle area is used, and fan speed is scheduled by PLA.

Digital Electronic Engine Control Flight Tests and Results

Flight testing of the DEEC began in 1981 in the NASA F-15 airplane, and continued into 1983 in

four separate phases. During the flight evaluation, several problems were found.³ The most significant problem was a nozzle instability that occurred during afterburning conditions at high altitude. This instability caused stalls and blowouts, and was not predicted by simulations or altitude facility tests.¹³ This instability was thoroughly investigated, and eventually eliminated with control system changes. By the end of the NASA tests, significant improvements had been demonstrated, with stall-free operation over the entire F-15 flight envelope, faster throttle response, improved airstart capability, and an increase of over 10,000 ft in afterburner operation, with no pilot restrictions on throttle usage. Figure 8 shows the DEEC idle-to-maximum power throttle transient results; all were successful, whereas, without the DEEC, the F100-PW-100 would experience stalls and blowouts above the indicated boundary.

The successful completion of the NASA DEEC test program allowed the USAF to put the DEEC into full-scale development and production. At the same time, an evaluation was initiated for the F-16 airplane, which was equally successful. Digital electronic engine control equipped engines have been flown in operational F-15 and F-16 airplanes and have demonstrated large improvements in performance, maintainability, and reliability. Thus, it is clear that the NASA-USAF flight evaluation in the NASA F-15 was key in the transition of the DEEC technology quickly into operational use.

Highly Integrated Digital Electronic Control Modes and Results

With the successful development of the DEEC and installation of the DEFCS on the NASA F-15 airplane, it was practical to integrate the engine and flight control systems. The HIDECS program integrated these systems and developed control modes to make use of the integrated system capability; these control modes and the flight results are discussed in the following sections.

Adaptive Engine Control System

As part of the HIDECS program, an adaptive engine control system (ADECS) mode was incorporated on the F-15 airplane. In ADECS, (Fig. 9) airframe and engine information is used to allow the engine to operate at higher performance levels at times when the inlet distortion is low and the full engine stall margin is not required. The ADECS mode increased thrust levels as shown in the fan map by increasing EPR at constant airflow (EPR uptrim). Fuel flow reduc-

tions could also be obtained by reducing the throttle setting to hold thrust constant as EPR was increased. In essence, ADECS traded unneeded stall margin for thrust.

In a recent flight evaluation, the ADECS mode was evaluated on the F100 EMD engines on the F-15 airplane. Significant performance improvements were demonstrated. Thrust improvements and constant thrust fuel flow reductions were determined, and compared to predictions. The ability of the ADECS to adapt to rapid aircraft maneuvers and throttle transients was also demonstrated. Intentional stalls were also conducted to validate the stability audit procedures used to develop the ADECS logic. Typical results are shown in Figs. 10(a) and 10(b), for an altitude of 30,000 ft. In Fig. 10(a), the calculated intermediate power thrust from the flight data matches the predicted thrust, with increases of 8 to 10 percent. In Fig. 10(b), the fuel flow reductions obtained at maximum thrust levels with the PLA reduced to hold constant thrust are shown; flight data matches predictions well, with decreases of 7 to 17 percent. These engine performance improvements resulted in airplane performance improvements (rate of climb, specific excess power) of 10 to 25 percent.⁴

Extended Engine Life Mode

The extended engine life (EEL) mode increases engine life by reducing turbine temperature. This reduction is accomplished by increasing EPR while decreasing engine airflow along a line of constant thrust, which reduces fuel flow and temperature.

The logic calculates a percent EPR uptrim command and an airflow downtrim using the following inputs: PT_2 and TT_2 , aircraft Mach number, angle of attack (α), and angle of sideslip (β). The commands are calculated in the DEFCS and sent to the engine's DEEC to produce the constant thrust EEL mode.

The EEL mode operates as shown in the block diagram of Fig. 11. The fan map shows that thrust lines are less steep than temperature lines, so by increasing EPR and reducing airflow, thrust can be held constant at reduced temperature. This operation nearer the fan stall line is modulated in real time on the F-15 airplane, and is only possible with an integrated system. The larger benefits occur at subsonic conditions, where the engine is not operating on the temperature limit.

The test approach used to evaluate the EEL mode was to perform two test points back-to-back, first to collect the baseline data and then the EEL data. Test

data were acquired at Mach numbers up to 0.9, and altitudes up to 40,000 ft.

The EEL mode successfully lowered the engine operating temperature while holding thrust constant to within 1 percent. Temperature reductions, shown in Fig. 12, ranged from 15 to 90°F. These temperature reductions were used to predict a 10- to 12-percent extension of engine life by the engine manufacturer.

The HIDECS technology is being incorporated in the F100-PW-229 increased performance engine and in other advanced engines. It is believed that the flight demonstration and evaluation were key in the rapid transfer of HIDECS technology into operational use.

Performance Seeking Control

Performance Seeking Control Compared to Highly Integrated Digital Electronic Control Performance seeking control (PSC) is a program which will feature an onboard real-time adaptive optimization of engine, inlet, and airplane parameters. Performance seeking control and HIDECS are compared in Fig. 13. As shown, the previously discussed HIDECS ADECS mode was developed off-line from extensive mathematical models of the engine and airplane. The integration schedules of optimum EPR were stored onboard in tabular form as a function of the flight and engine variables. As such, the EPR uptrim schedules were only optimum for the average engine operating with nominal bleed on a standard day.

Performance seeking control, on the other hand, uses many parameters in optimizing the cost function in real time onboard the airplane. It also uses a Kalman filter to identify key engine parameters, which are then used to update the engine model. In this way, the engine model can adapt to the actual engine and flight conditions being flown. More details of the PSC implementation on the NASA F-15 are shown in Fig. 14.

Parameter Identification

The adaptive capability of the PSC algorithm is provided by a Kalman filter estimator.¹⁴ The flight measurements used by the Kalman filter consist of four engine control and five engine response parameters. These parameters are compared with the predicted nominal engine operation and the Kalman filter is then driven by the difference. The Kalman filter provides estimates of five component deviation parameters (CDP) which represent the difference between the predicted and actual engine performance. Ideally, the CDPs represent changes in the (1) fan-low turbine ef-

efficiency, (2) fan airflow, (3) compressor–high turbine efficiency, (4) core airflow, and (5) core turbine area. In practice, however, the CDPs also contain the effects of modeling errors and unmodeled effects such as Reynolds number effects. Performance seeking control as developed for the NASA F-15 airplane has been constrained to use only the standard sensor set on the F100 DEEC engine, and cannot differentiate efficiency changes between the compression and turbine sections of a spool.

Compact Models

To solve the optimization problem, the CDPs are used with the measured variables in a steady-state linear model formulation of the engine to produce unmeasured engine parameters. The model is adjusted to the current flight condition using basepoint tables based on engine operating pressures. Nonlinear effects in the augmentor are also calculated.

The exhaust nozzle model calculates the internal nozzle performance and external boattail drag as a function of engine and flight conditions.

The inlet–trim drag model represents the performance of the inlet first ramp on inlet pressure recovery, drag, and pitching moment, and also the associated change in position of the horizontal tail, and its trim drag. The inlet third ramp effects on inlet drag and recovery are also modeled. The inlet and nozzle models are assumed to not change with time, and are not updated by the Kalman filter.

Optimization

The PSC algorithm then optimizes the combined system, including the engine, nozzle, inlet, and trim drag for the desired performance parameter, using a linear programming algorithm. The performance objectives (cost functions) available are:

1. Maximum thrust,
2. minimum fuel at constant thrust,
3. maximum engine life at constant thrust, and
4. maximum thrust at constant temperature.

Primary constraints of fan and compressor stall margin, temperature, and engine and inlet geometry form the boundaries for the optimization.

The outputs of the optimization are the two inlet variables; the cowl position and the third ramp posi-

tions, the nozzle area, engine fan and compressor variable vane positions, core and afterburner fuel flow, fan airflow, and fan speed. These parameters are computed as trims to the current control inputs and are sent to the DEEC and inlet control systems.

Predicted Performance

The predicted performance of the PSC on the F-15 airplane was determined for subsonic flight conditions, using the PSC digital simulation. Figure 15 shows the intermediate-power thrust improvement over the standard F100 EMD engine, both for the HIDECA ADECS mode and for the PSC maximum thrust mode. Performance seeking control offers 3- to 10-percent more thrust increase than ADECS. Figure 16 shows the breakdown of thrust improvement at one flight condition. The ADECS EPR uptrim represents 3 percent of the thrust increase. However, PSC adds an additional 9 percent; 5 percent because of the ability to optimize airflow, 1 percent each for optimizing the fan and compressor variable stator vanes, and 2 percent more for EPR uptrim to values higher than ADECS could achieve because of the Kalman filter adapting to the actual flight engine. Similar benefits are available at other flight conditions.

The first phase of PSC will be limited to subsonic conditions, where the inlet effects are not significant. In a later phase, the inlet will be incorporated in the optimization, and Mach numbers up to 2.3 will be flown. A prediction of thrust benefits at supersonic conditions is shown in Figs. 17(a) and 17(b). The thrust increase as a function of Mach number and altitude are shown in Fig. 17(a), and the breakdown of inlet, engine, and nozzle components of thrust are shown in Fig. 17(b). The thrust improvements, while not as large as those predicted for subsonic conditions, are potentially equally significant because of the smaller excess thrust at supersonic speeds.

Propulsion-Enhanced Flight Controls

Many multiengine airplanes can be controlled to some degree with only the propulsion system. There are many instances in which a total or near-total flight control system failure has occurred, and pilots had to use the propulsion system for flight control. With the advent of digital controls, it may be possible to develop an emergency flight control mode that uses only the engines. Because of the inherent low bandwidth of engines compared to flight controls, it is unlikely that good flying qualities can be obtained, but emergency landings may be possible. NASA Ames-Dryden is cur-

rently investigating the development of such an integrated flight-propulsion control mode, both for transport and high-performance fighter-type aircraft. Experience from the cooperative control, HIDEDEC, and PSC programs will be important in developing this capability. It is anticipated that flight validation will also be desired.

Technology Transition

Transition of NASA propulsion control-propulsion-flight control integration is shown in Fig. 18. The YF-12 research began in the early 1970's, flew in the late 1970's, and the concepts were implemented on the SR-71 in 1983. The DEEC research began in the mid-1970's, was flown in the early 1980's, and went into production for the F100-PW-220 engine in 1986. The HIDEDEC began with studies in the early 1980's, flew in the mid-1980's, and is now being applied to the F100-PW-229 and advanced engines. In all three cases, the flight demonstration and evaluation was a key part of the technology transition from the laboratory to production. Flight research exposes concepts to the real world environment, forcing all anticipated problems to be addressed. It also provides highly-visible and indisputable evidence of the validity of a concept. Moreover, if a concept passes the flight evaluation, the likelihood of getting it into production is sharply increased.

Concluding Remarks

Integrated propulsion-flight control and digital control research have been shown to have significant performance benefits for high performance and supersonic cruise airplanes. The YF-12 cooperative control flight research concept was implemented on the SR-71 fleet. Flight research on the digital electronic engine control (DEEC) system on the NASA F-15 airplane led to production use in the F-15 and F-16 airplanes. More recent highly integrated digital electronic control (HIDEDEC) flight research is now being applied to advanced engines. The flight evaluation and demonstration of these technologies have been a key part in the transition of the concepts to production and operational use on a timely basis.

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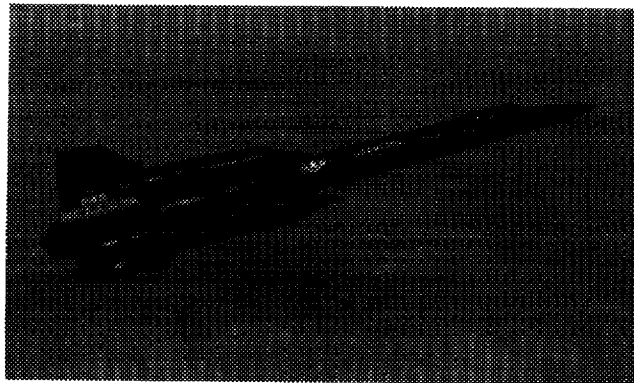
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Fig.1 Test airplane.

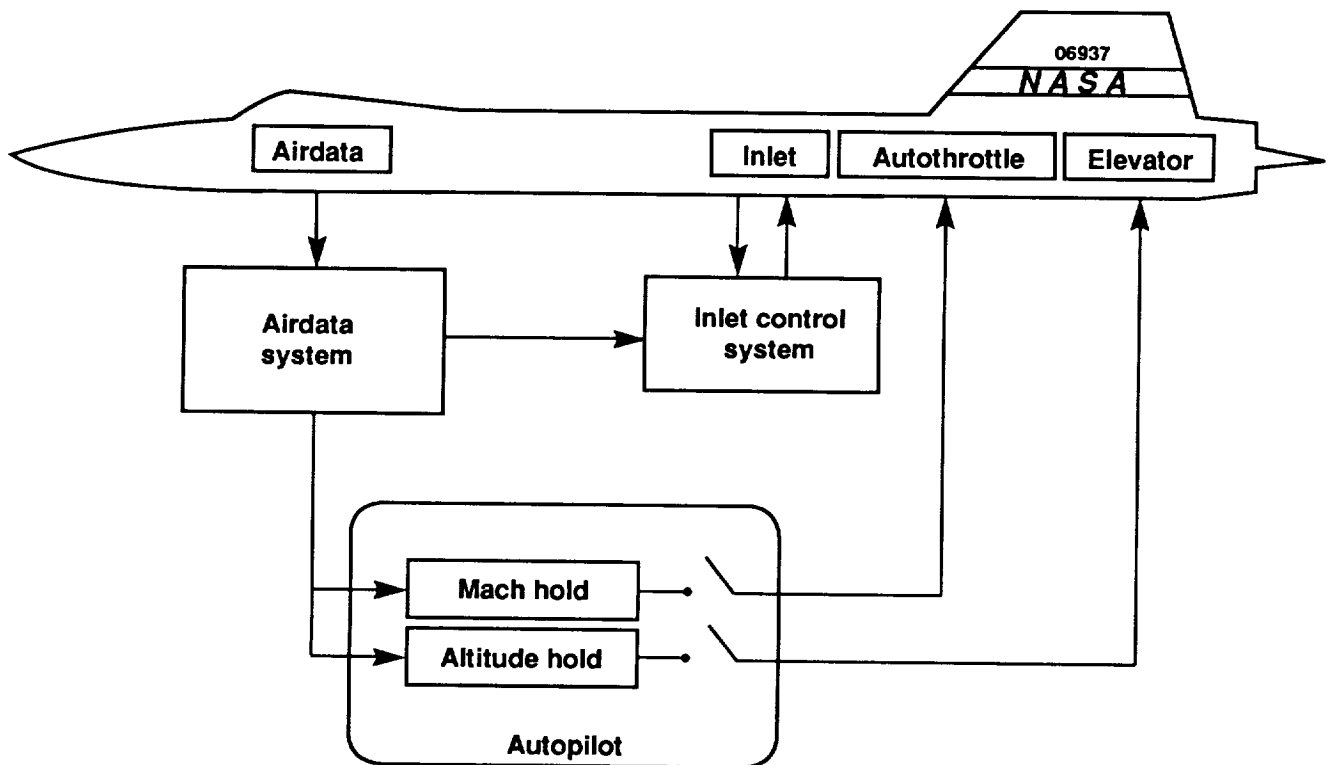
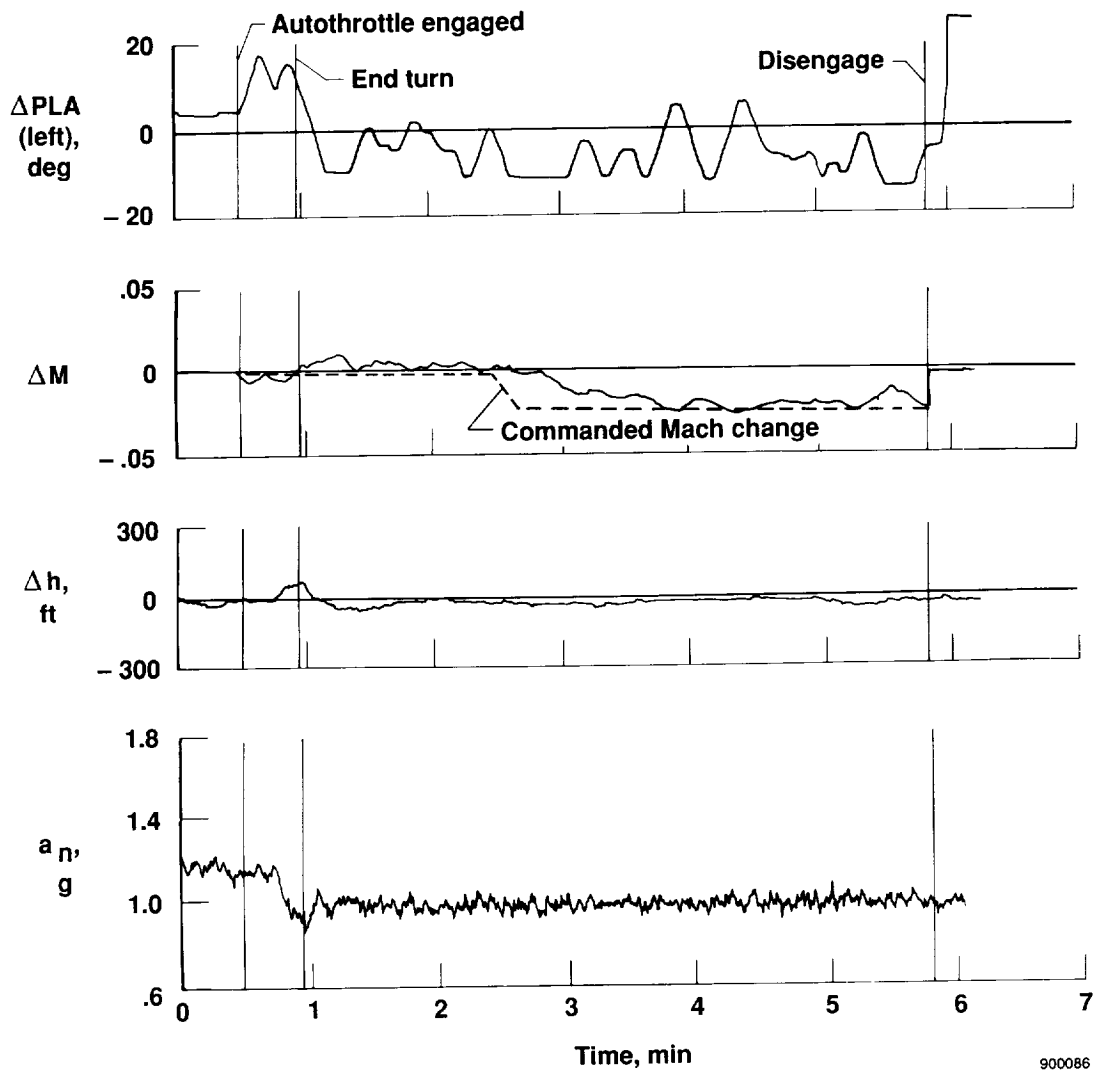


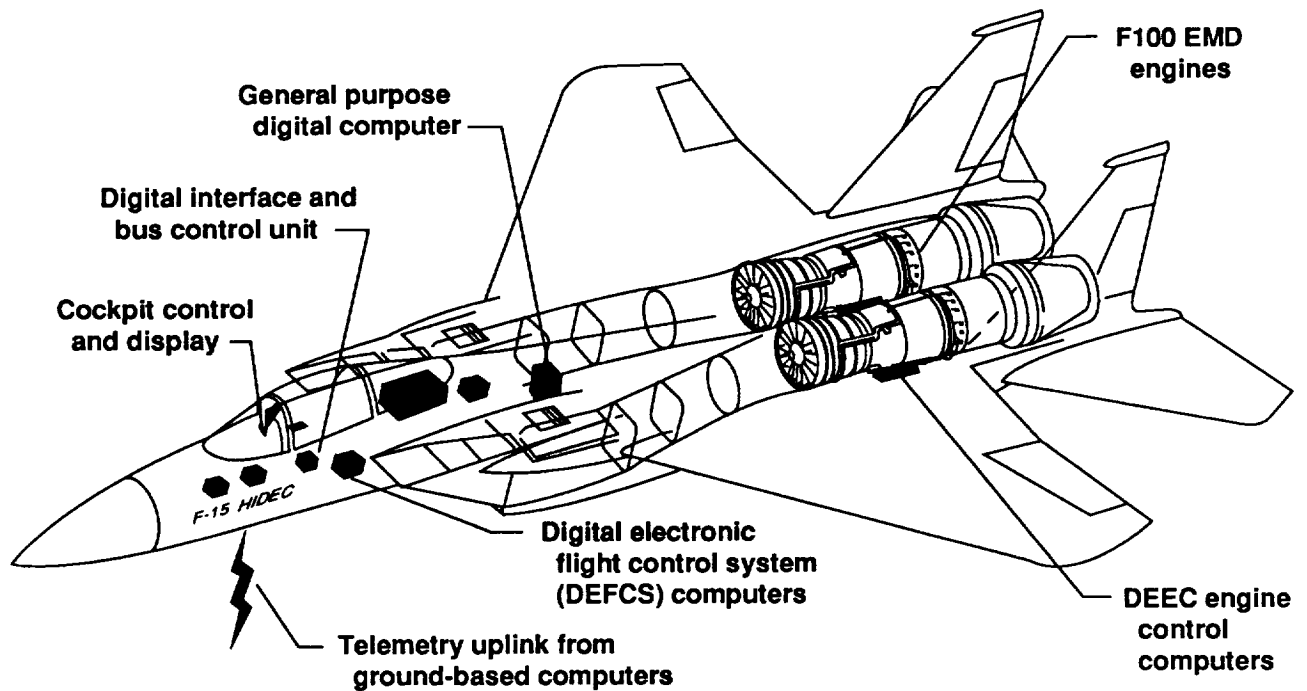
Fig. 2 YF-12 Program improved autopilot system.

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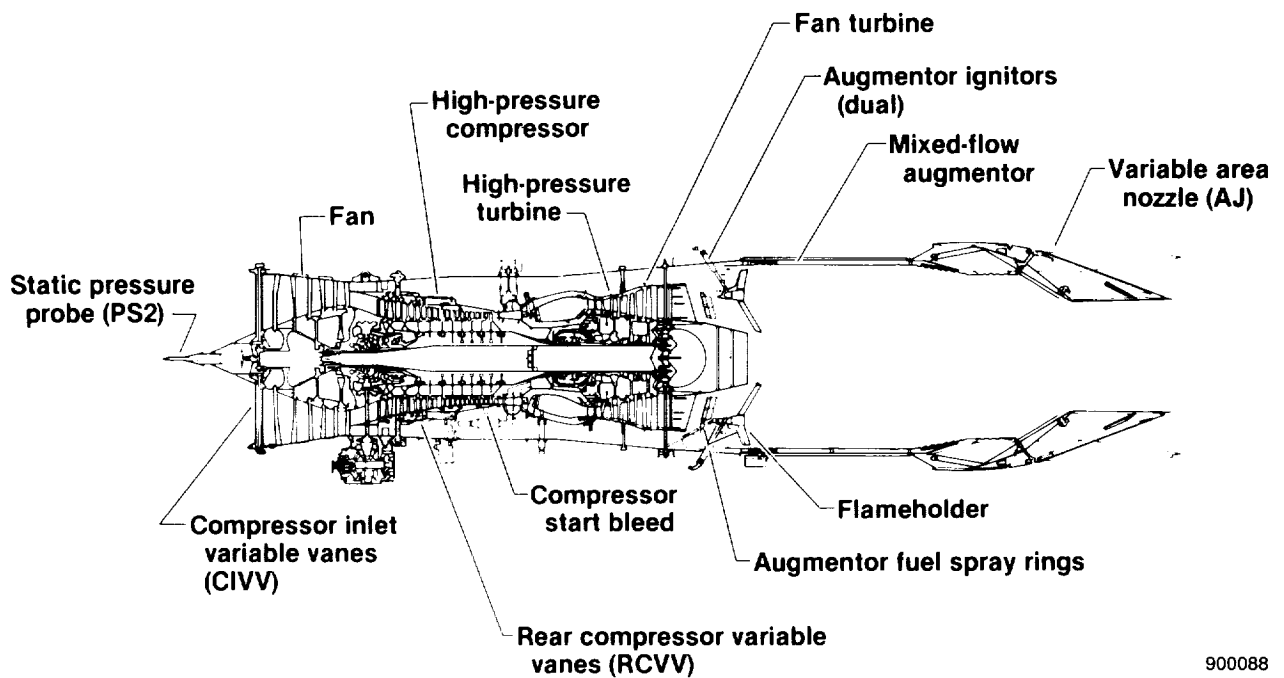
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Fig. 3 Time history of YF-12C flight with autothrottle, Mach hold, and altitude hold modes engaged. $M = 3.0$; 72,500 ft.



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Fig. 4 Features of the F-15 HIDEAC research airplane.



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Fig. 5 Section view of the F100 engine.

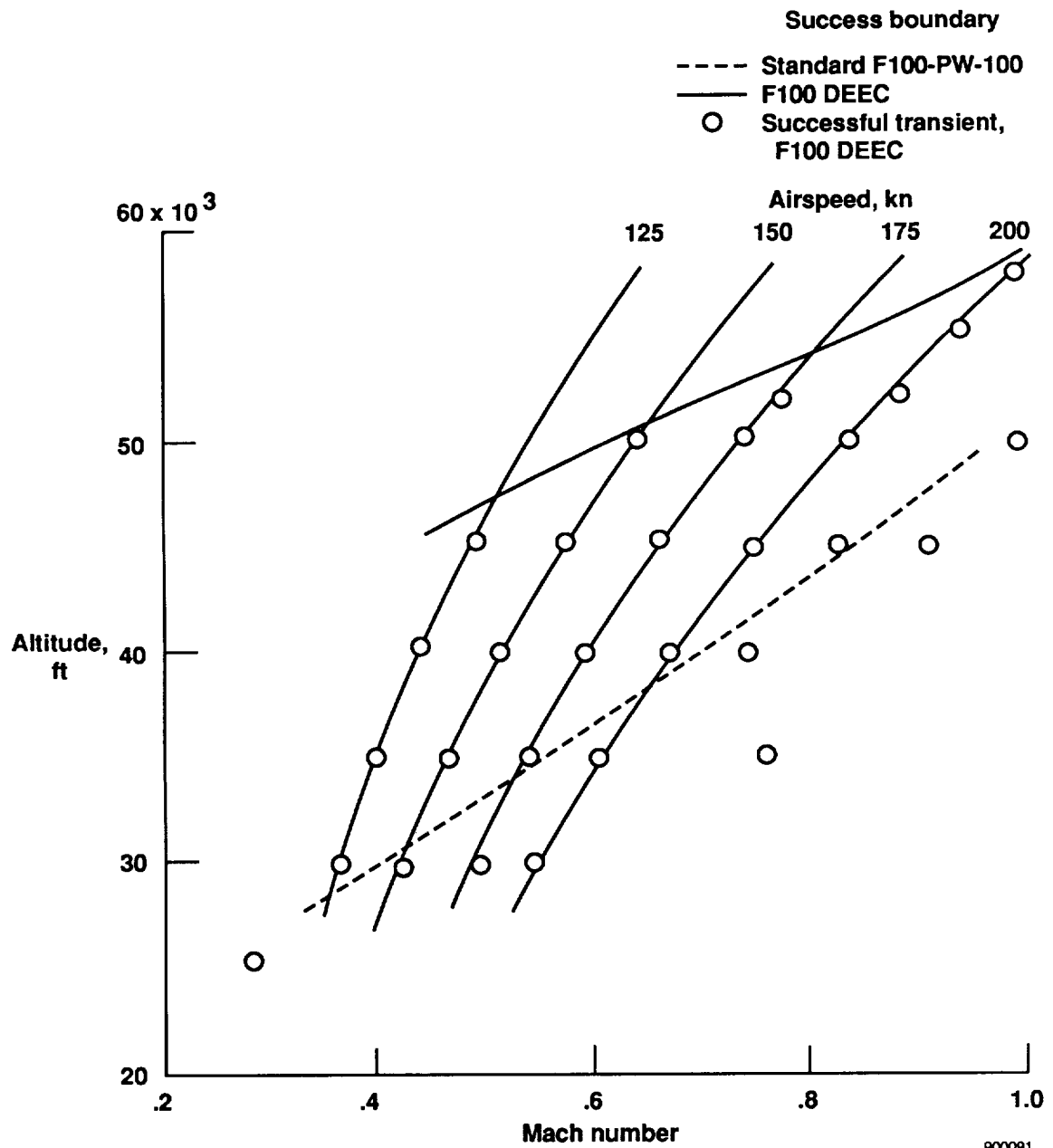
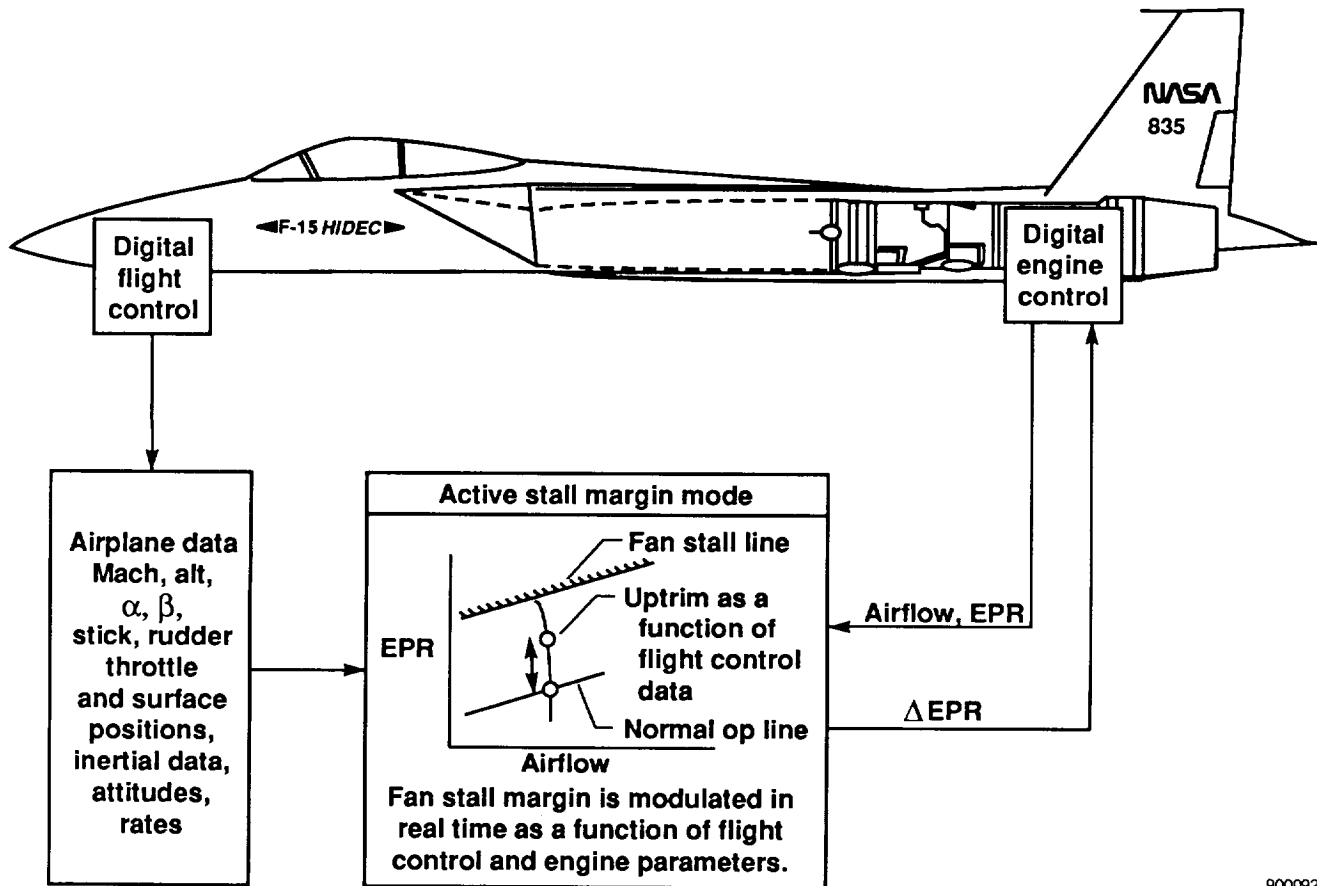
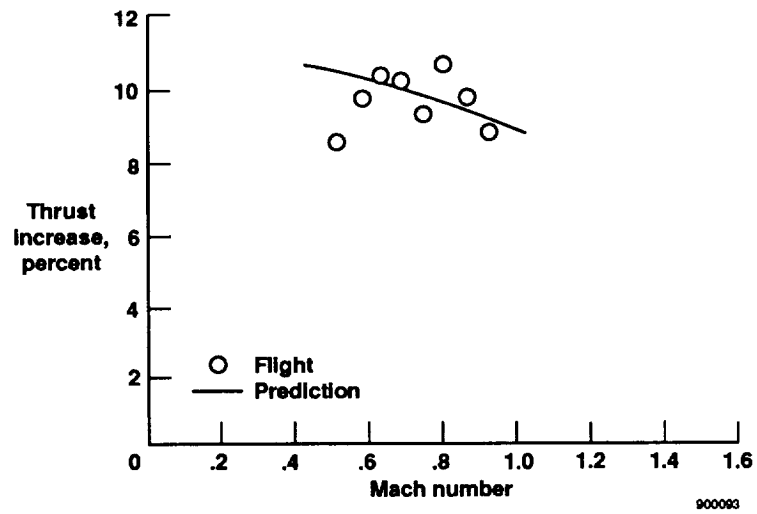


Fig. 8 Comparison of idle-to-maximum power throttle transients, for F100 DEEC and standard F100-PW-100.

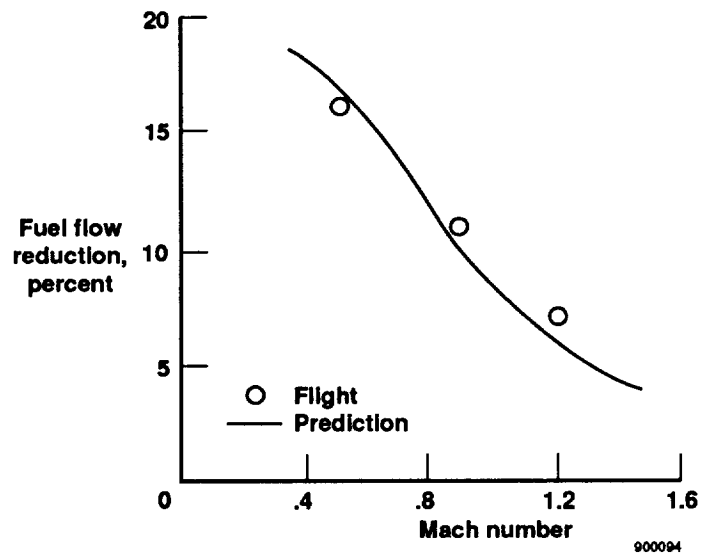


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Fig. 9 Schematic of HIDECS ADECS mode.



(a) Thrust increase at intermediate power.



(b) Reduction in fuel flow with uptrim to obtain nonuptrimmed maximum thrust.

Fig. 10 HIDEC flight results compared to prediction, 30,000-ft altitude.

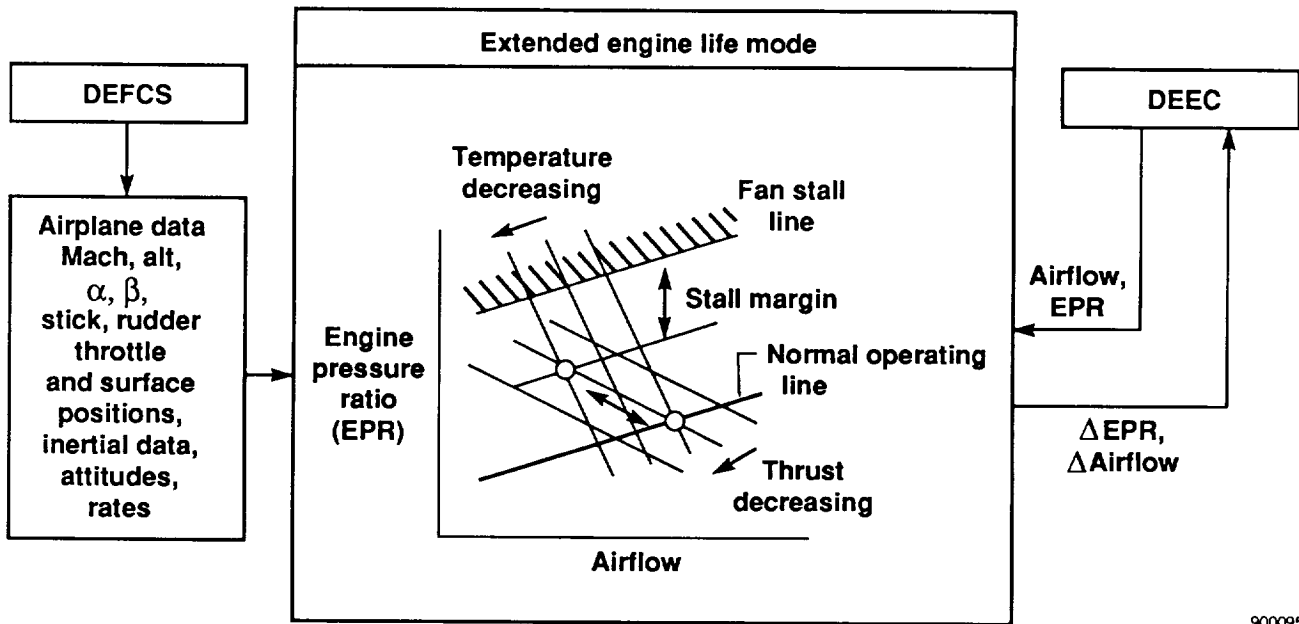


Fig. 11 Schematic of HIDE extended engine life mode.

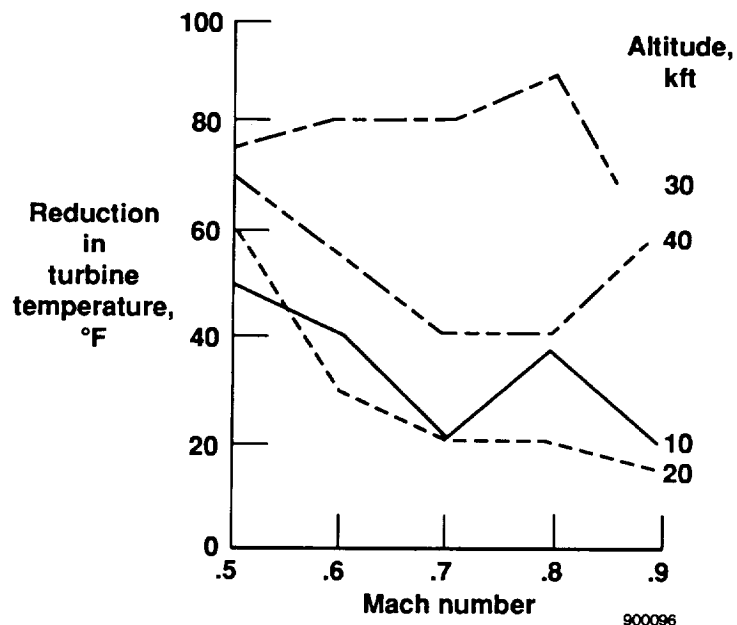


Fig. 12 Results of HIDE extended engine life mode, intermediate power.

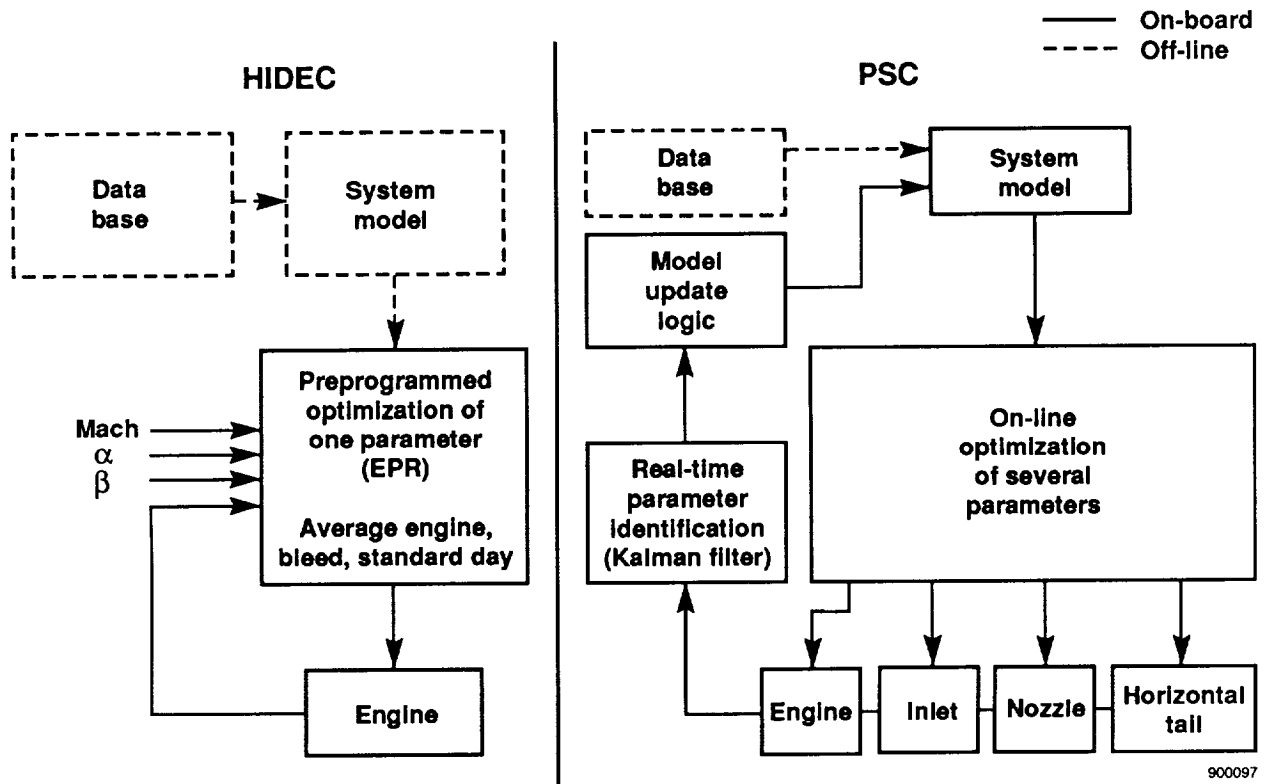
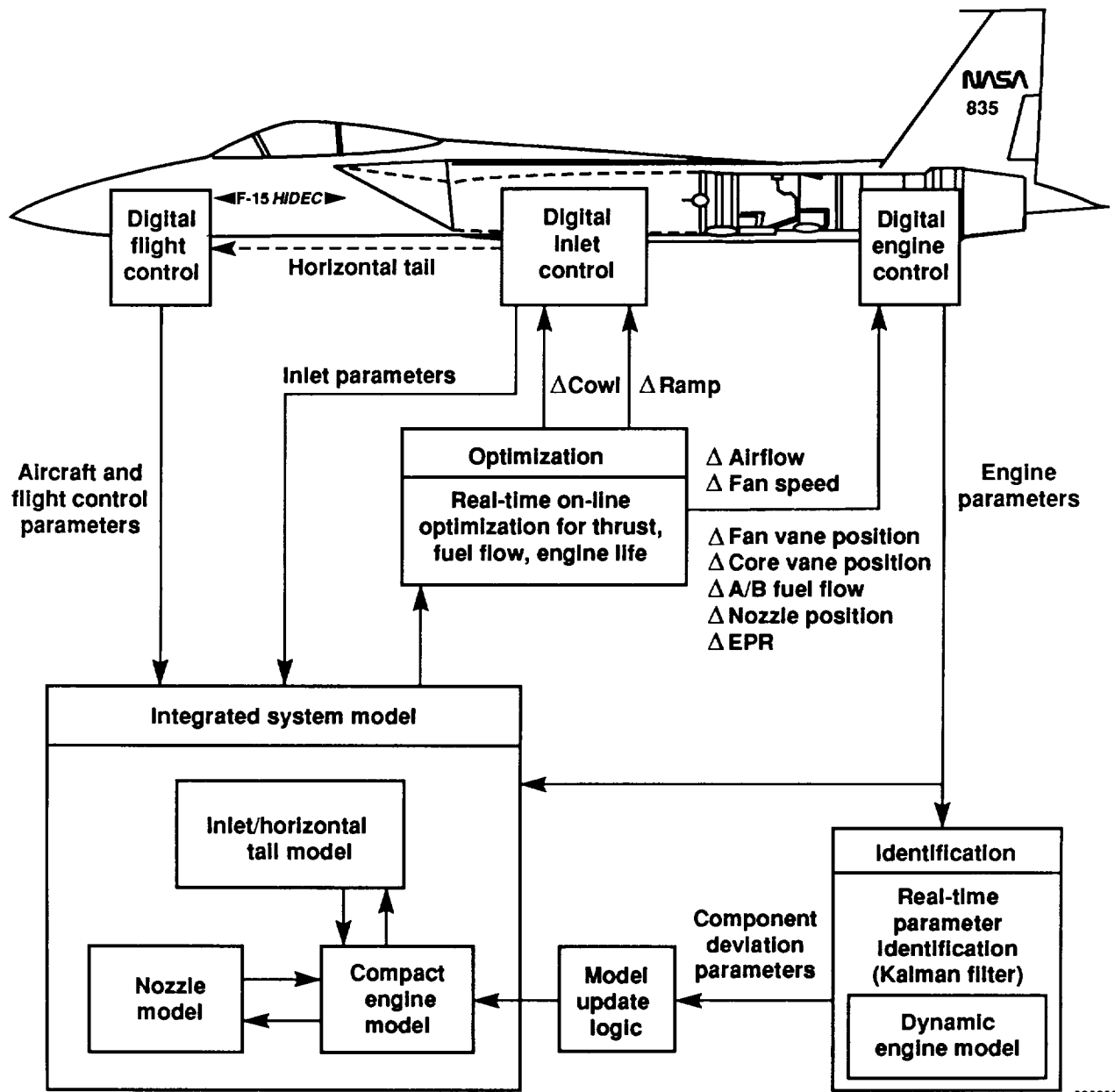


Fig. 13 Comparison of HIDEC and PSC block diagrams.



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Fig. 14 Schematic of PSC mode.

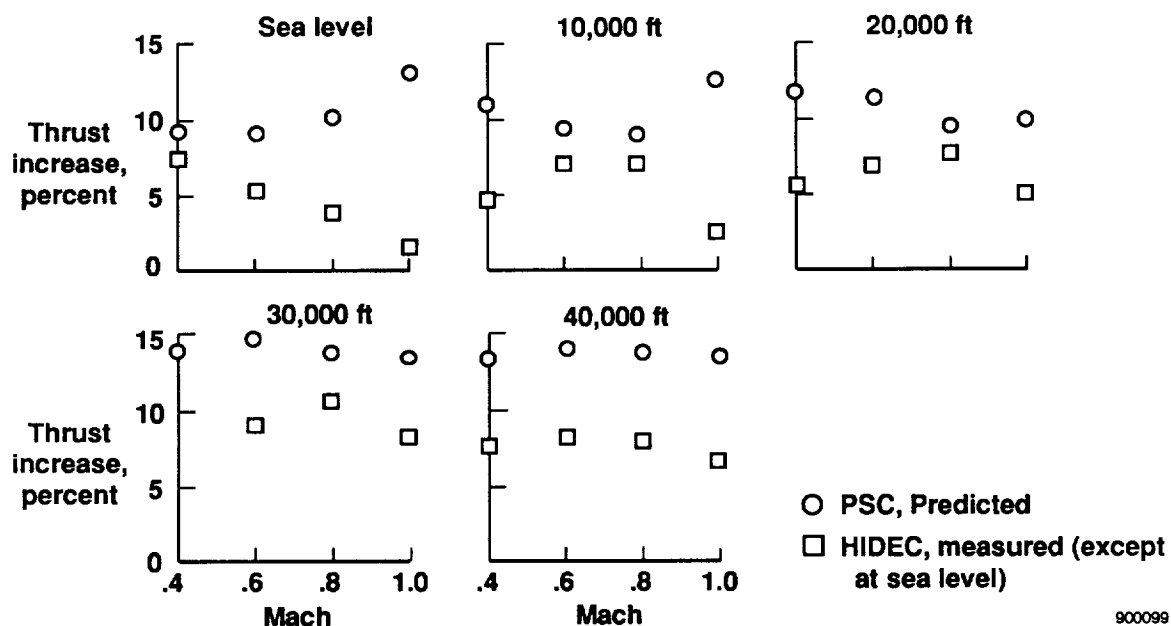


Fig. 15 Percent thrust improvements for HIDEDEC and PSC, intermediate power.

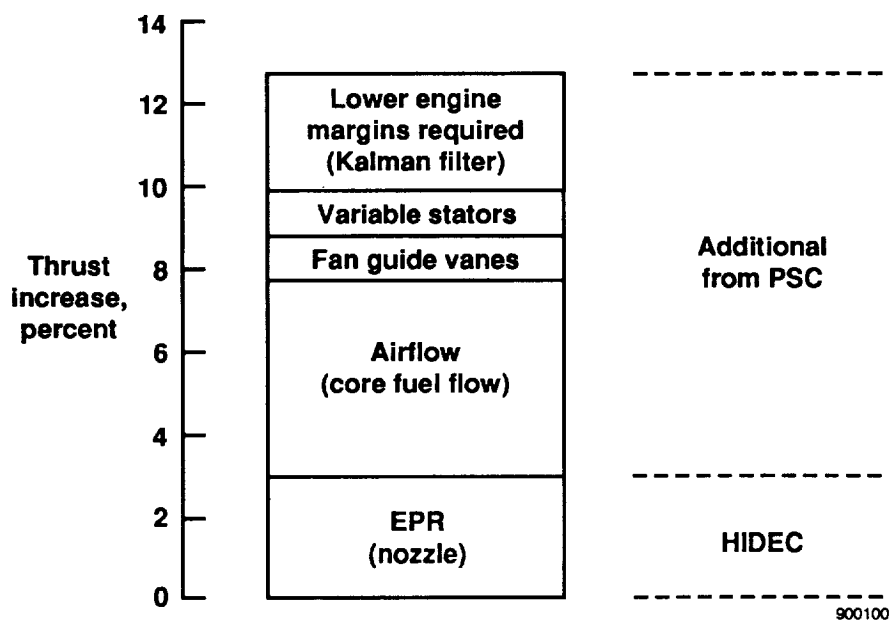
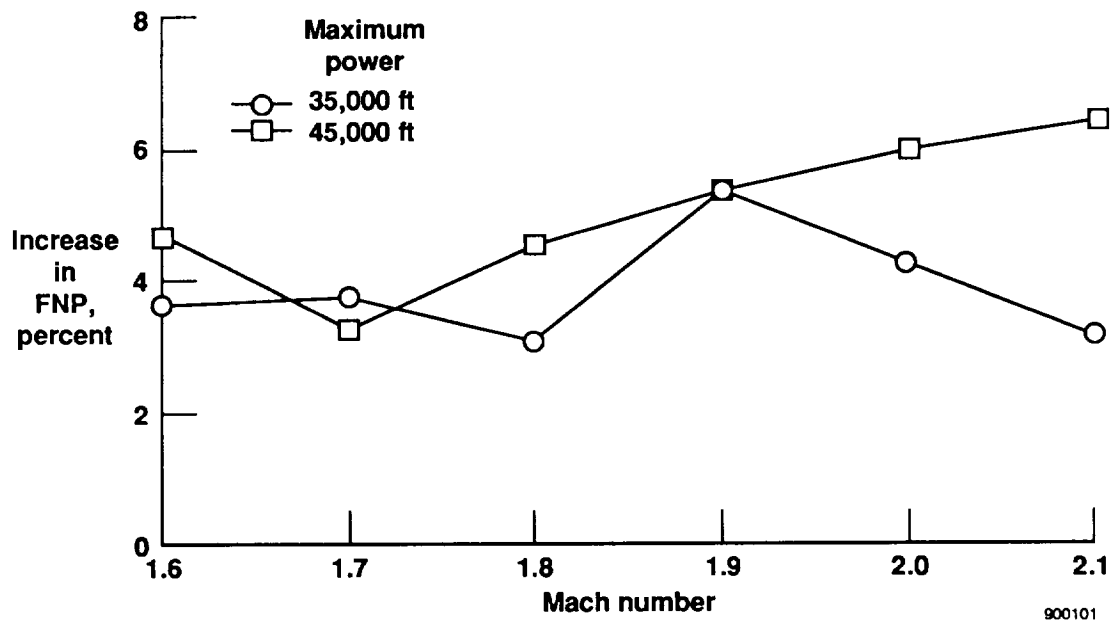
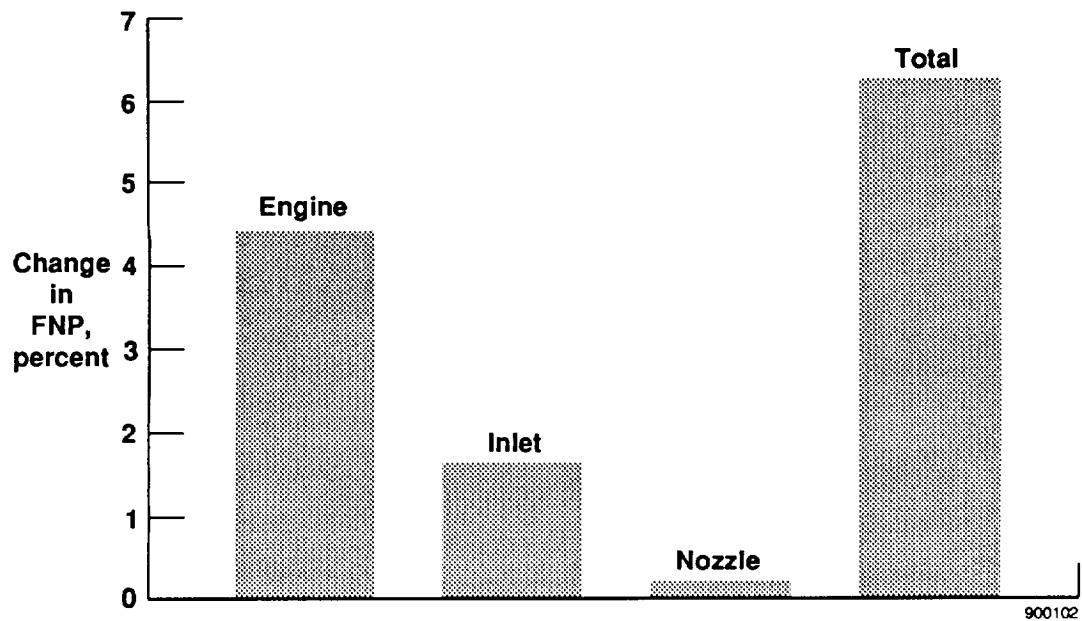


Fig. 16 Thrust increase breakdown for HIDEDEC and PSC, $M = 0.9$, sea level, intermediate power.



(a) Thrust increase.



(b) Thrust breakdown, $M = 2.1$, $H = 45,000$.

Fig. 17 Predicted PSC thrust improvements at supersonic conditions, maximum power.

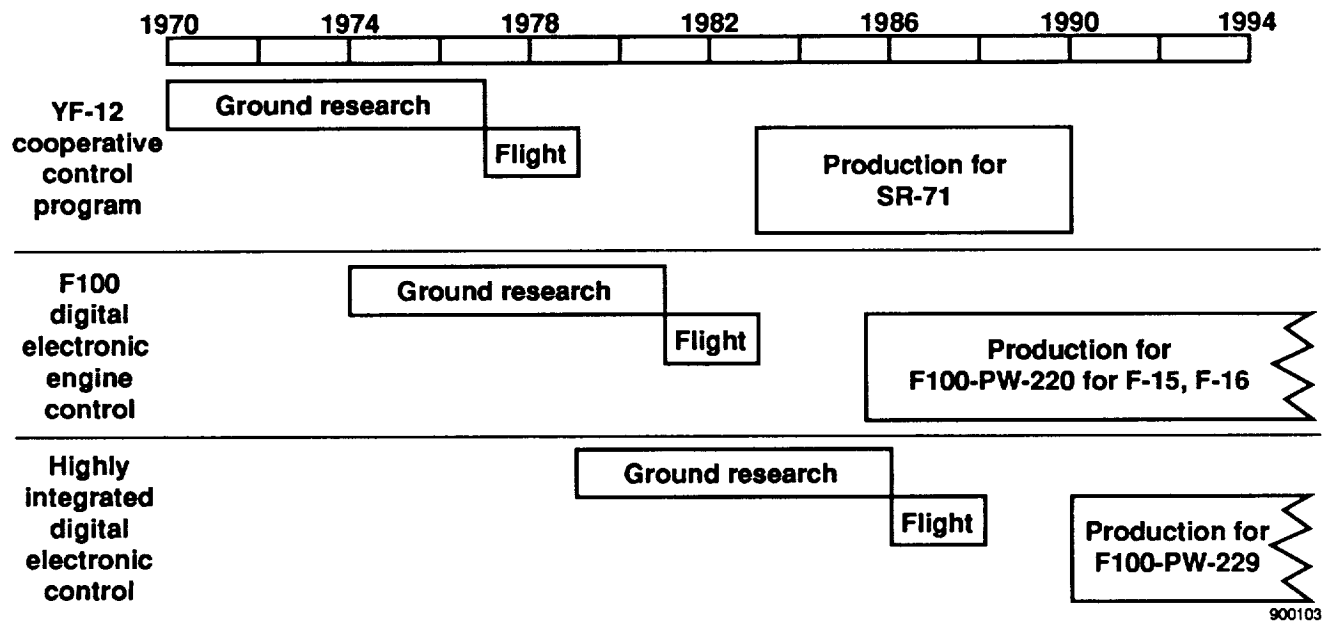


Fig. 18 Transfer of propulsion and propulsion/flight control integration technology from ground research to flight research to production.



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16. Abstract Integration of propulsion and flight control systems and their optimization offers significant performance improvements. The NASA Ames Research Center, Dryden Flight Research Facility has, over the years, conducted research programs which have developed new propulsion and flight control integration concepts, implemented designs on high-performance airplanes, demonstrated these designs in flight, and measured the performance improvements. These programs, first on the YF-12 airplane, and later on the F-15, have demonstrated increased thrust, reduced fuel consumption, increased engine life, and improved airplane performance; with improvements in the 5- to 10-percent range achieved with integration and with no changes to hardware. The design, software and hardware developments, and testing requirements have been shown to be practical. This technology has been transferred to the user community through reports, symposia, and industry cooperative programs, and is appearing on operational and advanced airplanes. The flight evaluation and demonstration have been shown to be key in maturing the technology and hastening its transition into production.			
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